# $W/Z+$ Jets and $W/Z+$ Heavy Flavor Jets at the Tevatron

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The associated production of jets and vector bosons is an important process at hadron colliders. An overview over recent Tevatron vector boson+jets measurements is given with an emphasis on comparisons between data and the predictions of various theory models.

## 1  Motivation

The associated production of jets and vector bosons ($V+$jets) in hadron collisions represents an important test of QCD. In addition, $V+$jets is a significant source of background events in many measurements and searches both at the Tevatron and the LHC. The development of simulation codes which produce accurate predictions for $V+$jets production has been a very active field of research over the last few years. The developments have followed two main paths: parton-level fixed-order predictions with NLO accuracy; and particle-level predictions from combining tree-level $2 \to N$ matrix elements with a parton shower algorithm. These new models require validation against experimental measurements of the properties of $V+$jets production. The leptonic decay modes offer distinct experimental signals with low backgrounds, and during the last two years a long list of $V+$jets measurements from the CDF and DØ experiments have been made public. All the measurements presented here are fully corrected for detector effects, thus offering a reference against which existing and future simulation models can be validated and tuned. The measurements can be divided into those which tag heavy-flavour (HF) jets and those which are inclusive in jet flavour.

## 2  $Z+$jets measurements

CDF has presented measurements of the jet multiplicity in $Z+$jets as well as the inclusive, differential $p_T^{\text{jet}}$ spectra in event with at least $N = 1, 2$ jets [1]. The boson is selected via its decay into an pair of high-$E_T$ electrons whose invariant mass is compatible with $M_Z$. Jets are defined using the Run II mid-point algorithm and are required to satisfy $p_T > 30$ GeV and $|y| < 2.1$. The correction for detector effects is deduced from a simulated event sample passed through a simulation of the detector. In Fig. 1 (left) the measured $p_T^{\text{jet}}$ spectra are compared with parton-level NLO pQCD predictions from MCFM [9] which have been corrected for hadronization and the underlying event. The NLO predictions are seen to agree with data within experimental and systematic uncertainties over one order of magnitude in $p_T^{\text{jet}}$ and four orders of magnitude in cross section.

DØ has presented measurements of the $p_T^{\text{jet}}$ spectra of the three leading jets in the $Z(\to e^+e^-)+$jets channel, normalized to the inclusive $Z(\to e^+e^-)$ cross section [2]. The event selection
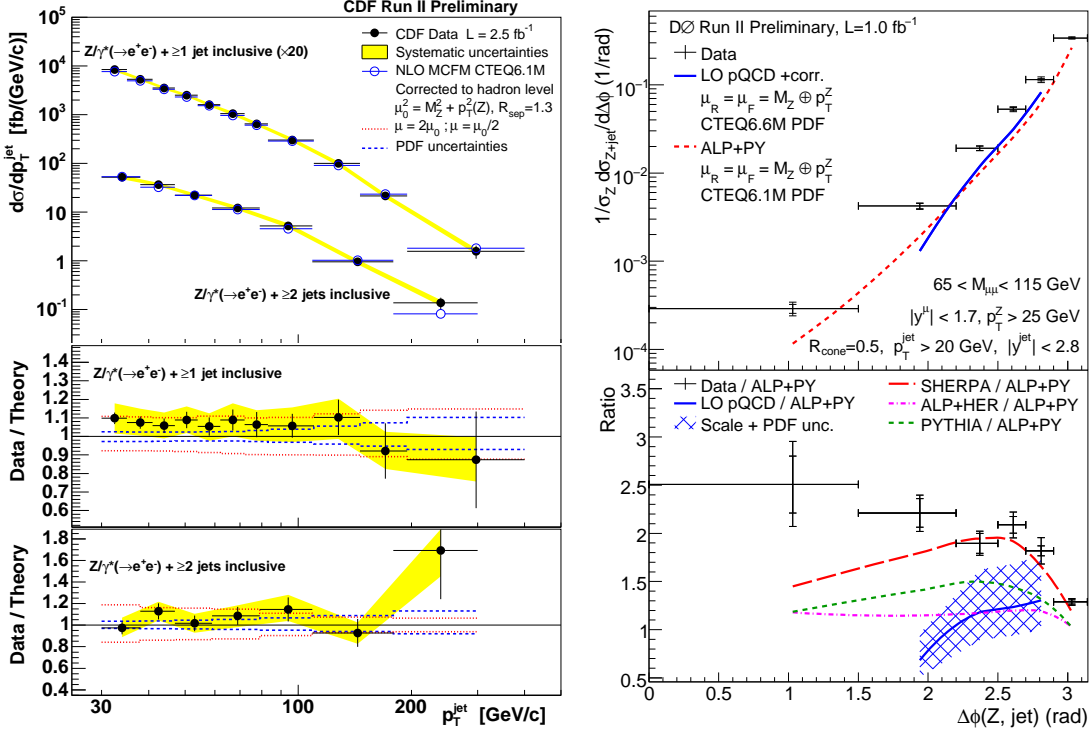
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Figure 1: Inclusive $p_T^{\text{jet}}$ spectra in $Z + N$-jet events, $N = 1, 2$, with data compared to NLO pQCD (right). Data compared with NLO pQCD and various event generators predictions for $\Delta\phi(Z,\text{jet})$ in $Z + 1$-jet events (left).

is similar to the CDF analysis, with jets being reconstructed down to 20 GeV. The measurements are compared with both with fixed-order pQCD parton-level predictions from MCFM and the particle-level predictions of various commonly used event generators. The comparisons for the second jet are given in Fig. 2. Both the LO and NLO pQCD predictions are consistent with data within experimental and theoretical uncertainties. As expected, the NLO prediction has significantly lower scale uncertainties than the LO prediction, corresponding to a higher predictive power. PYTHIA [10] using Tune A ("old" $Q^2$-order parton shower) predicts less jet activity than seen in data, and the discrepancies increase with $p_T^{\text{jet}}$ and jet multiplicity. The same tendency is seen for HERWIG [11]. PYTHIA using Tune S0 ("new" $p_T$-ordered parton shower) gives good agreement for the leading $p_T^{\text{jet}}$ spectrum, but no improvement over the old model for sub-leading jets. In contrast, both SHERPA [12] and ALPGEN+PYTHIA [13] are found to predict the shapes of the $p_T^{\text{jet}}$ spectra reasonably well for all three leading jets, with the latter generator giving somewhat better agreement for the leading jet. The normalizations are affected by significant scale uncertainties which increase with jet multiplicity. SHERPA (ALPGEN+PYTHIA) predicts more (less) jets than observed in data, but for both codes the normalizations can be made to agree with data by adjusting the choices of factorization and renormalization scales.

Two DØ studies [3,4] presents measurements of the $p_T$ and rapidity of the $Z$ and the leading jet, as well as various angular correlations between the two objects. The data are compared with NLO pQCD from MCFM, PYTHIA using Tune A, SHERPA, ALPGEN+PYTHIA using Tune A, and, for the angular correlation observables, ALPGEN+HERWIG. While fixed-order NLO calculations are found found give accurate predictions for $p_T$ and jet multiplicity observables (see above), it does not describe the spectrum of $\Delta\phi(Z,\text{jet})$ (Fig. 1 (right)) for values close to $\pi$, where multiple soft emissions are important, or below $\sim 2$, where the underlying event gives sizable contributions. Of the particle-level event generators, SHERPA is found to give the most accurate description of the angular correlations.
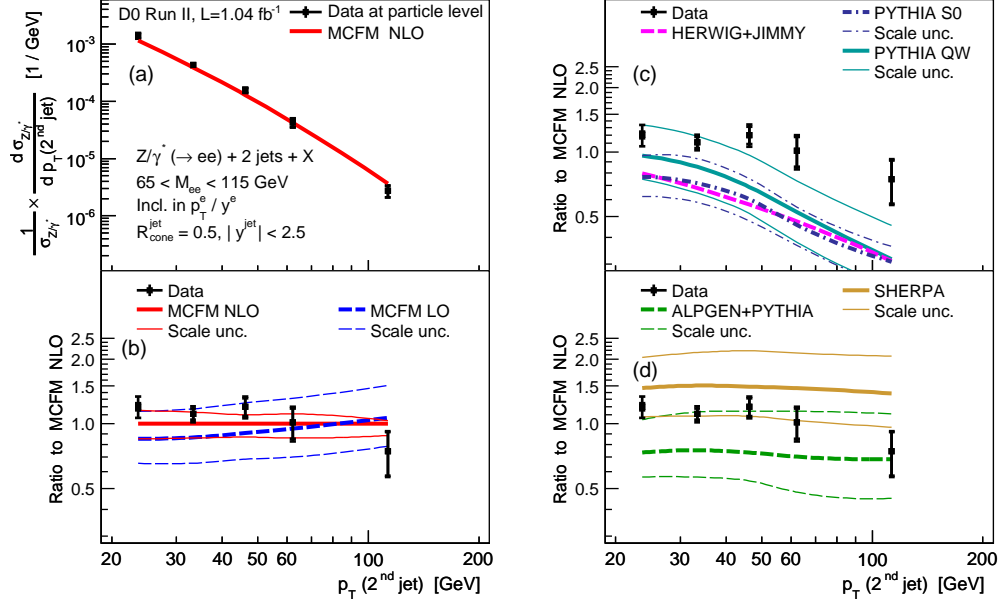
Figure 2: Data compared with NLO pQCD and various event generators predictions for $p_T(2^{nd}$ jet$)$ in $Z + 2$-jet events.

## 3   $V+$HF-jet measurements

Many searches for new particles, e.g. low-mass Higgs searches at the Tevatron, tag $b$-jets in order to enhance the signal to background ratio. In such searches, accurate predictions for the associated production of a vector boson and heavy-flavour jets is of major importance for the sensitivity of the analysis to new physics.

Both CDF and DØ have presented measurements of a $W$ boson in association with a single $c$ quark using similar strategies [5,6]. This channel is sensitive to the $s$-quark content of the proton at large $Q^2$, and it is a background to top-quark measurements and searches for a low-mass Higgs particle at the Tevatron. The $W$ is selected via a high-$p_T$ lepton ($e$ or $\mu$), and large missing $E_T$. A soft muon from a semi-leptonic $c$-quark decay is used to tag $c$-jets. For signal events the two leptons tend to have opposite charge, whereas the backgrounds show no such charge correlation. CDF measures $(\sigma \times \mathrm{BR}) = 9.8 \pm 2.8(\mathrm{stat})\pm^{+1.4}_{-1.6}(\mathrm{sys})$ pb, which is in good agreement with the NLO pQCD prediction of $11\pm^{+1.4}_{-3.0}$ pb. DØ presents the differential $p_T^{\mathrm{jet}}$ cross section for $W + c$ relative to $W+$jet and sees agreement with ALPGEN+PYTHIA within uncertainties.

Based on a similar event selection, CDF measures the $W + b$-jet cross section [7]. The $W$ is selected via its decay into $e\nu$ or $\mu\nu$, and a secondary-vertex algorithm is used to define a $b$-quark enhanced sample. The $b$-quark content is extracted from the secondary-vertex mass distribution by fitting with mass templates for light-flavour, $c$ and $b$ quark samples. The cross section for $p_T^{b-\mathrm{jet}} > 20$ GeV is measured to be $(\sigma \times \mathrm{BR}) = 2.78 \pm 0.27(\mathrm{stat})\pm 0.42(\mathrm{sys})$ pb. The ALPGEN prediction of the cross section is 0.78 pb, which is a factor of $3 - 4$ below data, and work is ongoing to understand this discrepancy.

A very similar $b$-tagging and $b$-content extraction technique is used by CDF in an analysis [8] of $Z + b$-jet events in the $ee$ and $\mu\mu$ channels. Cross sections are measured relative to the inclusive $Z$ cross section and are presented differential in $E_T^{b-\mathrm{jet}}$, $\eta^{b-\mathrm{jet}}$, $p_T^Z$ and jet multiplicity both for $b$ jets and flavour-inclusive jets. The total relative cross section is measured to be $\sigma(Z+\mathrm{jet})/\sigma(Z) = (3.32\pm0.53(\mathrm{stat})\pm0.42(\mathrm{sys})) \times 10^{-3}$. The NLO pQCD prediction is $2.3\times10^{-3}$ for $\mu_F^2 = \mu_R^2 = m_Z^2 + p_{T,Z}^2$ and $2.8 \times 10^{-3}$ for $\mu_F^2 = \mu_R^2 = \langle p_T^{\mathrm{jet}}\rangle^2$, in good agreement with data within uncertainties. The prediction of ALPGEN is $2.1 \times 10^{-3}$ and PYTHIA predicts $3.5 \times 10^{-3}$.
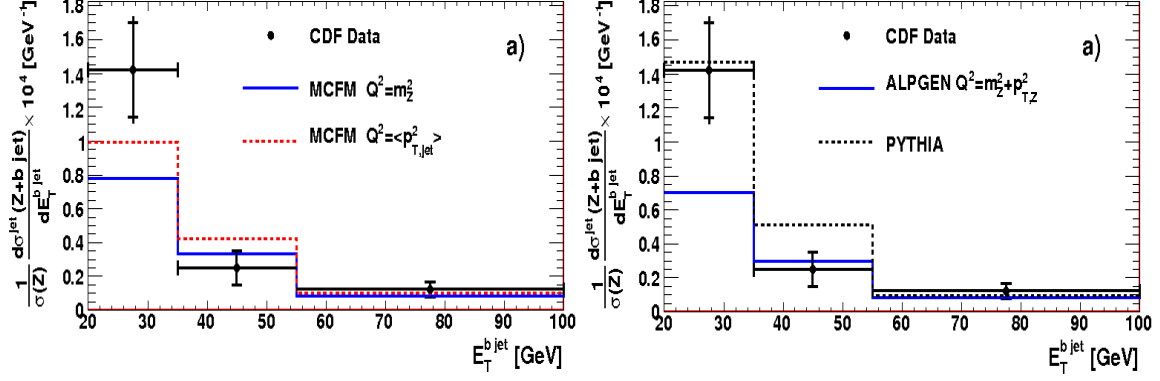
Figure 3: The $p_T^{b-\mathrm{jet}}$ spectrum measured in $Z + b$-jet production compared with MCFM, PYTHIA and ALPGEN.

The large difference between ALPGEN and PYTHIA has been traced back to the higher choice of scales used for ALPGEN than for PYTHIA.

## 4    Conclusions

In addition to offering an important test of QCD, $V+$jets production is a major source of background to many measurements and searches at hadron colliders. Several new codes for simulating the associated production of $Z/W$ and jets have become available over the last few years, and the validation and tuning of these tools are of great importance. A long list of $V+$ jets measurements have become available from the CDF and DØ experiments during the last two years. Parton-level predictions from NLO pQCD are found to offer the highest predictive power for $p_T^{\mathrm{jet}}$ spectra, showing good agreement with data, both for flavor-inclusive and HF measurements. Generators matching tree-level matrix elements with parton showers are found to offer the most accurate particle-level predictions but have significant scale uncertainties. Angular correlations show sensitivity to multiple soft emissions and the underlying event and are therefore partially outside of the scope of fixed-order pQCD calculations, and event-generator predictions show varying agreement with data. In the heavy-flavor channels, both pQCD and event-generator predictions are found to be in agreement with data within uncertainties, with a possible exception being $W + b$-jet production. Since all presented measurements are fully corrected for detector effects they can be directly used for testing and improving existing and future theory models.

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